iBalance-ABF: a Smartphone-Based Audio-Biofeedback Balance System

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Abstract— **This article proposes an implementation of a Kalman Filter, using inertial sensors of a Smartphone, to estimate 3D angulation of the trunk. The developped system monitors the trunk angular evolution during bipedal stance and helps the user to improve balance through a configurable and integrated auditory-biofeedback loop. A proof-of-concept study was performed to assess the effectiveness of this so-called iBalance-ABF - smartphone-based audio-biofeedback system - in improving balance during bipedal standing. Results showed that young healthy individuals were able to efficiently use ABF on sagittal trunk tilt to improve their balance in the ML direction. These findings suggest that iBalance-ABF system as a Telerehabilitation system which could represent a suitable solution for Ambient Assisted Living technologies.**

Index Terms — **Balance, Smartphone, Wearable device, Inertial motion unit; Biofeedback; Ambient Assisted Living**

I. Introduction

Inertial Motion Units (IMU) have been considerably developed during the last two decades. Their miniaturization, reliability along with their low-cost and low-power consumption have allowed their embedded use in many daily living items such as Smartphone. Their use was also extended to various applications (*e.g.*, gait [1], fall [2]). Traditionally, analyses of balance and gait postural stability are performed on a force platform and consist in monitoring the trajectories of the center of foot pressure during laboratory-based experiments [3]. This material is sophisticated, expensive, needs to be manipulated by a trained experimenter, and allows only occasional experiments which limits long-term monitoring or convenient follow-up care for balance-impaired people. Decrease in the balance abilities is often due to a loss, related to illness or ageing, in the functionality of one or several component(s) of their sensorymotor system. Thus, some training or rehabilitation balance programs proposed are based on sensory supplementation through visual (*e.g.*, [4]), auditory (*e.g.*, [5]), vibrotactile (*e.g.*, [6]) or even electro-tactile (*e.g.*, [7]) feedback. However, because of the material needed, such programs mainly take place in hospitals or specialized institutions. The advent of IMU has offered new possibilities for the assessment of postural and gait control [8], especially in daily living conditions. Moreover, IMU embedded in usual items such as Smartphone may not only be used to monitor [9] but also to detect fall or for long term measurements. The proposed Smartphone-based biofeedback (BF) balance system differs from this latter as the assessment of human movement relies not only on the embedded couple accelerometer/magnetometer, but also on the embedded gyroscope. This leads to more reliable angle determination and less sensitivity to magnetic disturbance. Interestingly, the so-called “iBalance” system we developed is “all-inclusive” since the 3 main components of the balance prosthesis, (i) the sensory input unit, (ii) the processing unit, and (iii) the sensory output unit, are entirely embedded into the smartphone. Furthermore, to meet users’ requirements, needs and/or preferences, we conceived the iBalance system as a multimodal interface that allows users to choose between 3 sensory modalities (visual, tactile, and auditory) to convey body movement information by using different coding algorithms. Since in the recent years, a growing number of studies have reported the effectiveness of audio-biofeedback(ABF)-based interventions for improving and training balance (see next section), we describe in this paper the design, the development, and initial assessment of the ABF-based mode of the iBalance system, the “iBalance-ABF”. The structure of this paper is the following. Section II discusses the related work on ABF balance system. Section III describes the iBalance-ABF system architecture. Section IV presents the experimental procedure and results of a proof-of-concept study designed to assess the effectiveness of the iBalance-ABF system. Section V draws conclusions and some directions to extend our work.

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II. Related works on ABF system for balance

ABF for balance has recently been the subject of much research. We sample some representative pieces of work from this literature, especially from Chiari and colleagues who developed a portable, accelerometry-based, ABF system [10]. They showed that auditory information related to trunk movement allowed healthy individuals and labyrinthine-defective patients to increase postural stability when sensory information from both vision and the surface were compromised by eye closure and stance on foam [11, 12], by strengthening the closed-loop control of posture [12]. Interestingly, compared to healthy individuals, labyrinthine-defective patients exhibited greater reduction of postural sway when standing on foam with eyes closed, suggesting that ABF could substitute for lack of vestibular information [5, 11]. Recent studies further demonstrated the usability and efficacy of ABF-based balance training in patients with progressive supranuclear palsy [13] and in patients with Parkinson's didease [14]. Taken together, these results, that are very promising to implement home-based training programs to improve balance capacities, encouraged us to develop an ABF-based balance system *entirely* embeeded on a smartphone. The ABF system used in [13, 14] included differents elements: a specific sensing unit based on a 3D accelerometer and gyroscope attached on the lower back by a velcro was used to measure trunk acceleration, which was wirelessly transmitted to a PDA. This PDA was responsible for real-time signal processing to modulate a stereo sound used to supply the user with complementary information about their trunk sway through headphones connected to the PDA.

III. iBALANCE SYSTEM ARCHITECTURE

The iBalance-ABF system is a smartphone-based ABF balance system that offers to its user a wireless, portable, lightweight and low-cost balance testing and rehabilitation training tool suitable for Home use (Fig. 1, real-time biofeedback loop, blue arrow). The iBalance-ABF system also allows the rehabilitation team (*e.g.*, medical doctors, physical therapists) to quantitatively and objectively assess the patient's balance ability remotely and in real-time, to create a customized balance training program by adaptively configuring and adjusting the system BF parameters (*e.g.*, balance exercise difficulty) based on each patient's individual ability/progress/needs/preferences and/or goals, and to track patient's progress history and compliance in order to improve quality of care (Fig. 1, remote monitoring loop, red arrow).

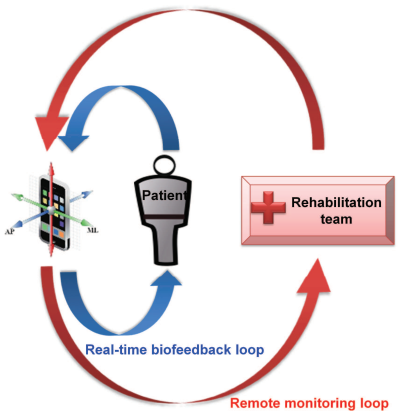

Fig. 1. iBalance system architecture.

The underlying principle of the iBalance-ABF system is to supply the user with supplementary information about the medial-lateral (ML) trunk tilt relative to a predetermined adjustable "dead zone" (DZ) through sound generation in earphones. In this section, we describe : (A) the sensory input unit, (B) the algorithm for angle estimation, and (C) the algorithm for BF generation.

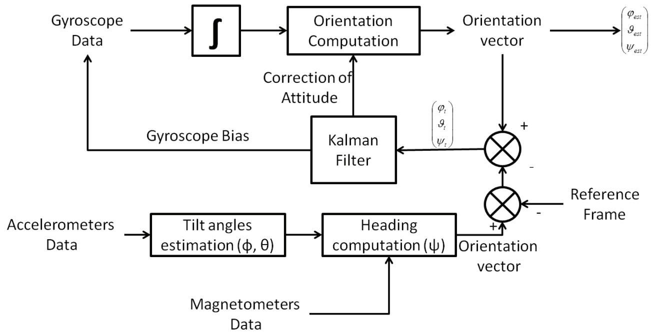

Fig. 2. Description of the process used for body 3-D orientation estimation.

A. Sensory input unit

The sensing unit we used is a smartphone (Apple iPhone 4) equipped with 3 distinct MEMS sensors: (1) a 3D accelerometer (ST-Microelectronics, LIS331DLH) that mostly senses the translation movement and can give information on tilt during static periods; (2) an integrated 3D gyroscope (ST-Microelectronics, L3G200D), that measures angular velocity; and (3) a 3D magnetometer (Asahi Kasei Microdevices, AKM8975) that provides information on angular rotations due to the measure of the Earth magnetic field (known and fixed). These 3 sensors form a 3D axes system illustrated on Fig. 1.

B. Algorithm for angle estimation

Angle estimation with IMU is a relatively well-explored theme [15]. From the 3 sensors, we can obtain measurement that can be used to compute the orientation of the sensor board in 3D. However, none of these sensors bring a noiseless and complete information. As a consequence, this information is used to update and maintain a Kalman Filter, allowing to estimate the bias of the gyroscope and, as a consequence, to compute a better estimate of the three angles. Fig. 2 shows the computation of the 3 angles. The complete description of the filtering process is described in [16]. Our request for the software was to be able to run at 100Hz. To allow this frequency on this device, we optimized the memory use and the computations (using tables for trigonometry).

As described in figure 2, accelerometers are first used to compute tilt angles (θ and φ). Then, magnetometers are used to estimate the heading (ψ). Another process estimates the 3 angles modifications by integrating the gyroscope data. As we have to integrate these values, a bias will appear (summation of the errors), due to the noise of the component, temperature, *etc*. These 2 estimations are then compared, to compute the difference between both. This difference is used as observation variable in the Kalman Filter that is used afterwards. From the output of this filter, we extract an estimated orientation variation (with the 3 modified angles θ_t, φ_t and ψ_t). These 3 angles are then corrected in the Kalman filtering process to give an estimate of the rotation angles θ_{est}, φ_{est} and ψ_{est} , that represent the rotation of this solid body (the smartphone) comparing to the reference, that is the mean position in the 5 first seconds of the postural trial.

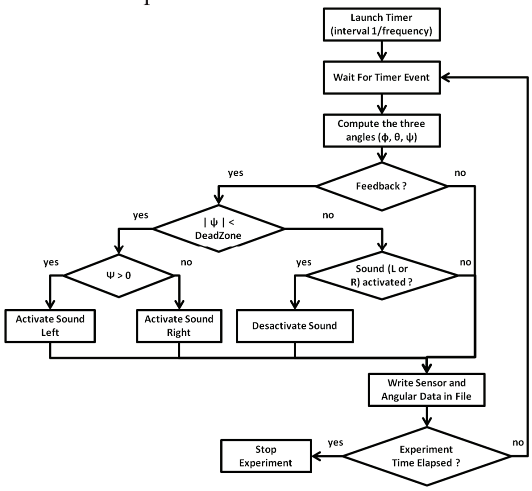

Fig. 3. Algorithm for ABF generation used in the proof-of-concept study.

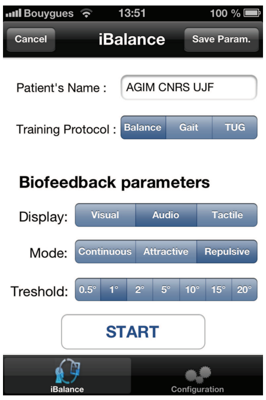

Fig. 4. Screenshots of iBalance application.

C. Algorithm for biofeedback generation

As for existing ABF balance systems, the DZ is considered to be a zone in which an individual sways while standing, but still does not need any extra information to stabilize upright posture. It is when swaying outside this DZ that an individual need to receive ABF to correct sway to within the DZ in order to stabilize upright posture [10]. In our proof-of-concept study, ML direction has been chosen since it has been proved that posturographic parameters of sway in that direction is the most strongly associated with fall risk in elderly population (*e.g.*, [17]), and the ML DZ size was set to 1°. As illustrated in Fig. 3, a "threshold-alarm" type of ABF was used: (1) when the ML trunk orientation was determined to be within the DZ, no ABF was provided to any of the 2 earphones; (2) for the entire time the ML trunk orientation was determined to be outside the DZ, *i.e.* when it was most needed, ABF provided a sound to either the left or the right earphone depending on whether the actual trunk orientation was exceeding the DZ in either the left or right direction, respectively. Interestingly, this "repulsive" ABF instructional cuing allows the activation of distinct and exclusive ear for a given ML trunk tilt with respect to the DZ. Note that the iBalance-ABF software (Fig. 4) was implemented to allow the algorithm of ABF generation and the DZ size to be easily and quickly modified according to the specific use of the iBalance-ABF system (*e.g.*, user's balance ability, needs, preferences).

IV. EXPERIMENTS AND RESULTS

A proof-of-concept study was designed to assess the effectiveness of the iBalance-ABF system in improving balance during bipedal standing.

A. Participants

Twenty healthy volunteers (9 males and 11 females; 26.5±3.7 years) voluntarily participated in the experiment. None of them presented any history of sensory and/or motor problems, neurological diseases or disorders. Participants all gave written consent for their participation. The experimental procedure was in accordance with the Helsinki Declaration and was approved by the local ethics committee.

B. Experimental protocol

Participants, arms close to the trunk, stood barefoot, with their eyes closed. They wore the smartphone mounted in a belt on the posterior low back at the level of L5 vertebra and a pair of earphones throughout the experiment. They were asked to sway as little as possible in 2 stances conditions: (1) feet parallel 10 cm apart, and (2) tandem stance (feet heel to toe), and 2 experimental conditions: (1) "No ABF" and (2) "ABF". In the latter condition, participants performed the postural task using the iBalance-ABF system. Six 30-s trials for each experimental condition were performed. The order of presentation of the 4 experimental conditions were randomized. Participants were not informed about their postural performances.

C. Data collection and analysis

Four dependent variables were used to describe participant's postural behavior: (1) the root mean square trunk tilt in the ML and AP directions (RMS in dregree), (2) the energy of the angulation signal in the ML and AP directions (in deg), (3) the 95% spectral edge frequency of the trunk tilt in the ML and AP directions (SEF95 in Hz), and (4) the duration of instability expressed as the time elapsed outside the DZ (error time in s). To evaluate the postural effect of ABF, these parameters were subjected to separate two-tailed paired-samples t-tests. Level of significance was set at 0.05.

D. Results and discussion

In the Parallel stance condition, no significant difference between No ABF and ABF conditions was observed ($Ps>0.05$, Fig. 5A-D, left panels).

In the Tandem stance condition, ABF yielded : (1) a significant decreased trunk tilt RMS in the ML direction ($P<0.01$), whereas no significant change was observed in the AP direction ($P>0.05$) (Fig. 5A, right panel); (2) a significant decreased energy in the ML direction ($P<0.05$), whereas no significant change was observed in the AP direction ($P>0.05$) (Fig. 5B, right panel) ; (3) a significant increased SEF95 in the ML direction (P<0.01), whereas no significant change was observed in the AP direction (P>0.05) (Fig. 5C, right panel), and (4) a significant decreased error time (P<0.01).

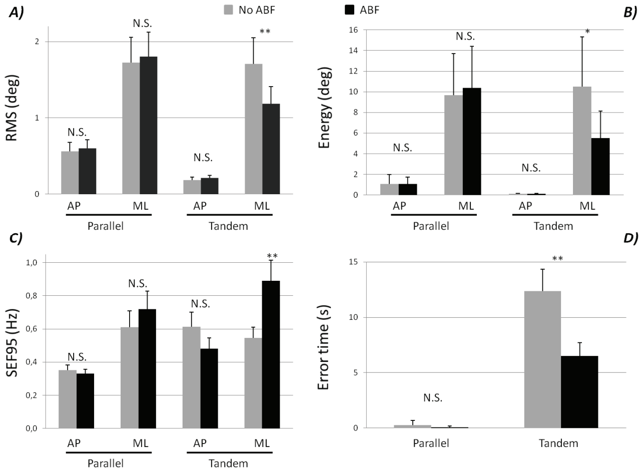

Fig. 5. Mean and standard error of mean of the RMS trunk tilt (A), Energy (B), 95%-spectral edge frequency (C) and error time measured in 2 stances (parallel and tandem) and the 2 ABF conditions (No ABF and ABF) (P values for comparison between No ABF and ABF conditions are reported: NS: P>0.05; *:P<0.05; **:P<0.01.

V. Conclusion

Results of the proof-of-concept performed on 20 young healthy subjects showed that, in absence of visual cues and in a stance which enhances lateral postural instability, healthy individuals were able to efficiently use ABF on sagittal trunk tilt to improve their balance in the ML direction. This immediate improvement of the control of bipedal posture is in line with previous studies of effects of ABF on stance posture in healthy subjects [10]. Interestingly, the iBalance-ABF we used is not a *dedicated* and *specialized* equipment for assessing and training balance, but *entirely* embeeded on a smartphone. Smartphones are fully embedded in daily life ; they are accessible, portable, affordable and iBalance seems useful and usable since sampled data could be easily transfered to the rehabilitation team which could, in turn, propose and monitor adapted and personalized training exercises to the patient (see Fig. 1). At this point, however, additional validation studies are required to evaluate whether the beneficial effect observed in the present proof-of-concept study in young healthy adults also occurs across people showing less accurate postural capacities (*e.g.*, elderly persons) and for whom the consequences of an impaired balance could be more dramatic. In addition, the choice of biofeedback signals does depend on the user requirements and sensory capabilities/deficits and undoubtedly plays an crucial role in ensuring its effectiveness. For instance, the provision of ABF is not suited for deaf patients. The iBalance system having been designed to provide various sensory cues, as recently done by [18], we have developed a Smartphone-Based Vibrotactile Audio-Biofeedback Balance System which is currently assessed. To conclude, we believe that the iBalance system we developed as a Telerehabilitation system could represents a suitable solution for Ambient Assisted Living technologies that could facilitate the necessary shift from intra- to extra-mural care and cure and could decrease healthcare costs.

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